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Land-use related organic matter dynamics in North Cameroon soils assessed by ^{13}C analysis of soil organic matter fractions

J. Sevink[a], F. Obale-Ebanga[b] & H. A. J. Meijer[c]

[a]*IBED, University of Amsterdam, Kruislaan 318, 1098 SM Amsterdam, The Netherlands,* [b]*Centre for Environment and Development Studies, PO Box 410/IRAD PO 33 Maroua, Cameroon, and* [c]*Centre for Isotope Research (CIO), University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

Summary

Topsoil samples from cultivated and adjacent non-cultivated fields on three major agricultural soils in North Cameroon were fractionated into particle-size fractions that were analysed subsequently for their C and ^{13}C contents. The aim was to obtain further insight into the dynamics of soil organic matter (SOM) in relation to land use in Cameroon. Since organic carbon contents of the fractions were often very small, samples and analyses were extensively replicated to obtain robust statistical estimates of observed differences. For each soil type, differences in $\delta^{13}C$ values between fields could be related to changes in the input and decomposition of organic matter arising from soil type, land management and, for example, the nature and abundance of weeds. Turnover of organic matter appeared to be fastest in the sand fraction, which is in line with results from earlier studies. In the finer fractions, clear differences in reaction to changes in input and decomposition were observed, that seem to be linked to differences in clay mineralogy. The results illustrate that SOM in the various fractions is much less stable and more strongly affected by changes in land use than might be assumed on the basis of changes in total SOM contents alone. At the same time, they demonstrate the relevance of ^{13}C isotope analyses of SOM for studies on the impact of land use on these savannah soils with little SOM that are highly susceptible to degradation.

Introduction

In North Cameroon, continuous cultivation causes widespread soil degradation (Brabant & Gavaud, 1985; Seiny-Boukar, 1990). Based on a comparative study of soils from fields with different land use histories, Obale-Ebanga (2001) showed that this is connected with small decreases in soil organic matter (SOM) contents, particularly in the sand fraction, with negative impacts on soil aggregation and aggregate stability. However, the dynamics of the SOM could be defined in general terms only (Obale-Ebanga *et al.*, 2002). The objective of this study was to obtain further information on its dynamics through a study of the carbon isotopic composition of SOM size fractions.

Trees and most temperate grasses using the C_3 photosynthetic pathway incorporate less ^{13}C than C_4 plants (mainly Gramineae in tropical regions). Thus, changes in vegetation from C_3 to C_4 plants or vice versa may lead to a corresponding change in the $\delta^{13}C$ value of SOM (commonly expressed as its $\delta^{13}C$ value), as for example reported by Schwartz *et al.* (1986) and Balesdent *et al.* (1988). Such changes are to be expected for the agricultural soils of North Cameroon, since sorghum and maize are important C_4 plants, while most other crops (beans, cotton) and the savannah trees and shrubs are C_3 plants.

Soils under tropical grasses (C_4 Gramineae) generally have $\delta^{13}C$ values ranging from −17 to −9‰ with mean values around −12‰, while forest soils with C_3 plants show values of −32 to −20‰, with mean values around −27‰ (Veldkamp, 1994; Pessenda *et al.*, 1996). However, heterogeneity in the vegetation often results in a wide range of intermediate $\delta^{13}C$ values for SOM indicating a mixed input from C_3 and C_4 plants.

Upon changes in land use, affecting the relative inputs from C_3 and C_4 plants, the largest changes in $\delta^{13}C$ values occur in the surface soil layer where conditions are most favourable for rapid turnover of organic matter (Schwartz *et al.*, 1986; Veldkamp, 1994). Changes are most prominent in the sand

Correspondence: J. Sevink. E-mail: j.sevink@science.uva.nl
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fraction with reported half-lives of < 12 years, whereas organic matter in clay and fine silt fractions is relatively stable (Balesdent *et al.*, 1987, 1988; Martin *et al.*, 1990).

Superimposed on the changes induced by changes in vegetation, two other processes might influence δ^{13}C values (Balesdent *et al.*, 1988; Martin *et al.*, 1990): (i) isotopic heterogeneity of the plant constituents, and (ii) isotopic fractionation that occurs during mineralization. However, from the scarce literature on these processes we conclude that in our soils fractionation or heterogeneity in terms of resulting differences in δ^{13}C are of a lesser order than the differences in isotopic composition between C_3- and C_4-plant litter inputs.

Our research was therefore aimed at showing whether isotopic analysis of the SOM size fractions might provide further information on the provenance and stability of SOM in savannah soils, in relation to land use.

Materials and methods

Sites and soils

The study area is the Diamare Plain in North Cameroon, with a tropical wet–dry climate. There is a short rainy season (June–September) and the annual rainfall is 800–900 mm. The Diamare Plain is a peneplain bounded in the west by the more humid Mandara Highlands and in the north and east grading into a lacustrine plain forming part of the drier Lake Chad basin.

Brabant & Gavaud (1985) and Bocquier (1973) described the main soil types (names in parentheses after FAO, 1988): ‘Sols ferrugineux lessivés’ (Chromic Luvisols) and ‘Vertisols’ (Vertisols), with intermediate ‘Planosols’ (Planosols) and ‘Sols fersiallitiques lessivés/differenciés’ (mostly Stagnic and Albic Luvisols). Chromic Luvisols abound on the upper pediment slopes, exhibit clear textural differentiation, but lack a prominent eluvial horizon. In the Planosols and Stagnic/Albic Luvisols, horizons are strongly differentiated with slightly acidic albic horizons, abruptly overlying a more acidic and clayey Bt horizon. Vertisols in recent sedimentary deposits (including the lacustrine plain) are described as ‘Hydromorphic Vertisols’ and are very recent soils that still regularly receive some fresh sediment. They lack the very dark colour and often prominent nodular calcic horizon of the upland Vertisols on the lower peneplain slopes. Three major land use types occur: (i) continuous dry-season cropping of sorghum (*Sorghum bicolor* (L.) Moench), (ii) wet-season cropping with cotton (*Gossypium hirsutum*) in rotation with sorghum (above) and other cereal crops, and (iii) fallow/pasture.

Dry-season sorghum, cultivated with zero tillage and without fertilizer, is the major crop on the Vertisols; a culture described as ‘Muskwari’. Sorghum seedlings are transplanted at the beginning of the dry season and grain is harvested after about 4 months. During the wet season, vegetation consists mainly of grasses, in particular *Setaria pumila* whose seeds are resistant to fire. This grass vegetation is slashed and burned just before transplanting. Innovations have led to some Muskwari soils being ploughed and some earth bunded to harvest rainfall. Most Muskwari fields have been under intensive crop production for more than 70 years. This constitutes the ‘Muskwari-based land use history’.

Cotton and cereal crops, particularly sorghum and maize (*Zea mays* L.), are cultivated in rotation on the Luvisols and Planosols, and to a lesser extent on the Vertisols. The soils are ploughed to 20–30 cm depth and mineral fertilizer is applied (annually 10–20 kg ha^{-1} NPK or more). Continuous cotton and cereal production for about 8–10 years usually alternates with a period of 6–10 years natural fallow. This constitutes the ‘cotton-based land use history’, now practised in North Cameroon for more than five decades. It is this land use in particular that causes a rapid decline of soil productivity as evidenced by low crop yields and compaction of soil surfaces.

Fallow land and natural savannah vegetation are generally used extensively by grazing cattle, sheep and goats: this is the ‘silvo-pastoral or fallow land use history’. For our study, three sites were selected from a larger series of sites, each comprising several adjacent fields with differences in land use history on a specific soil. The sites selected cover the major agricultural soils and land use types in North Cameroon. General site characteristics are presented in Table 1 and general analytical data in Table 2. Details of the area, its land use and land degradation are given by Brabant & Gavaud (1985) and Obale-Ebanga (2001).

Sampling

Four small plots (circles of 2 m radius) were selected randomly within an area of 0.25 ha within a specific field. From each plot, three samples were taken randomly from the topsoil (0–5 cm) and bulked by plot. Because of the scarcity of reliable data on the land use history of individual fields, and of land with prolonged fallow (all soils) or bunded fields (in the case of the ‘Muskwari’), and of the local variability in soil properties, sampling of the chosen sets of fields was not replicated.

Organo-mineral size fractions

Air-dried soil was sieved at 2 mm. The > 2 mm fractions were very small, consisted entirely of mineral fragments and therefore were discarded. Bulk fine earth fractions were completely free of carbonates. Procedures used to separate 53–2000 μm and < 53 μm fractions were after Gavinelli *et al.* (1995). Briefly, 20 g (Vertisols) or 40 g (Luvisols) < 2 mm air-dried soil was soaked in 240 ml sodium hexametaphosphate solution (0.5 g l^{-1}) and shaken for 3 hours (Vertisols) or 1 hour (Luvisols). The soil suspension was sieved over a 53-μm aperture sieve and the remaining material washed repeatedly. The suspensions of the < 53 μm fractions were made up to 1 litre and ultrasonicated at 60 W for 7 minutes. Cylinders containing

Table 1 Sites studied and their general characteristics

Site and soil (FAO)	Field	Land use history
Flat part of	Vm	'Muskwari' (*Sorghum bicolor* (L.) Moench); > 70 years
dissected lower pediment	Vf	8 years Fallow after prolonged Muskwari (> 60 years). Shrub layer: dominant *Acacia seyal* and *Ziziphus mauritiana*; herb layer: *Andropogon* species
Chromic Vertisol	Vc	Cotton (*Gossypium hirsutum*), latest crop; in rotation with wet-season sorghum (*Sorghum bicolor* (L.) Moench); about 9 years
Almost flat upper pediment slope	Lf	21 years Fallow: open savannah vegetation. Shrub layer: *Acacia seyal*, *Combretum glutinosum* and *Piliostigma reticulatum*; herb layer: *Loudetia togoensis*, *Hyparrhenia ruffa* and *Andropogon chinensis*
Chromic Luvisol	Lr	10 years Cereal crops: cowpea (*Vigna unguiculata*; latest crop) in rotation with sorghum and maize (*Zea mays* L.)
	La	10 years Agroforestry with *Acacia albida* (tree) and cotton (latest crop) in rotation with sorghum
Almost flat lower	Mt	Traditional Muskwari: Continuous slash and burn (> 70 years)
pediment slope	Mb	Muskwari with bunds: Slash and burn combined with earth bunding (about 20 years), after traditional Muskwari (> 50 years)
Hydromorphic Vertisol	Mp	Muskwari ploughed: No slash and burn, but incorporation of stubble and weeds by ploughing (20 years), after traditional Muskwari (> 50 years)

Table 2 Chemical and physical properties of the topsoils ($n = 4$; values in parentheses are standard deviations)

Field	Depth /cm	pH (H_2O)	pH ($CaCl_2$)	EC /μS cm^{-1}	Organic C /%	C/N
Vm	0–5	7.1 (0.3)	6.4 (0.2)	56.1 (13.9)	0.650 (0.11)	16.35
	5–15	7.4 (0.4)	6.7 (0.4)	50.6 (20.6)	0.463 (0.04)	16.82
	15–30	7.5 (0.3)	6.8 (0.4)	56.8 (27.7)	0.428 (0.05)	20.60
Vf	0–5	7.0 (0.2)	6.3 (0.2)	47.0 (19.1)	0.800 (0.16)	15.24
	5–15	7.2 (0.2)	6.6 (0.3)	46.4 (19.5)	0.563 (0.04)	17.05
	15–30	7.7 (0.2)	6.9 (0.3)	51.9 (18.6)	0.470 (0.04)	15.16
Vc	0–5	7.3 (0.2)	6.5 (0.3)	49.7 (31.6)	0.630 (0.10)	15.53
	5–15	7.3 (0.3)	6.5 (0.5)	38.6 (21.1)	0.610 (0.05)	15.19
	15–30	7.6 (0.3)	6.5 (0.7)	43.5 (21.9)	0.540 (0.05)	17.00
Lf	0–5	7.0 (0.6)	6.3 (0.6)	32.7 (6.1)	1.103 (0.22)	11.82
	5–15	6.9 (0.9)	6.0 (1.1)	21.0 (9.7)	0.815 (0.14)	8.93
	15–30	6.9 (0.8)	5.9 (1.2)	24.2 (15.1)	0.618 (0.11)	9.96
Lr	0–5	6.0 (0.2)	5.1 (0.2)	16.3 (2.1)	0.690 (0.04)	8.93
	5–15	6.0 (0.1)	4.8 (0.2)	11.7 (2.1)	0.770 (0.08)	10.48
	15–30	6.2 (0.2)	4.9 (0.3)	10.0 (1.1)	0.588 (0.05)	8.80
La	0–5	6.9 (0.8)	6.2 (0.9)	24.1 (6.3)	0.635 (0.07)	8.82
	5–15	6.8 (1.0)	5.8 (1.1)	17.8 (4.1)	0.665 (0.05)	9.78
	15–30	6.5 (0.8)	5.5 (1.2)	12.9 (2.6)	0.503 (0.20)	8.93
Mt	0–5	7.2 (0.6)	6.4 (0.6)	72.7 (26.5)	0.760 (0.07)	8.49
	5–15	7.1 (0.5)	6.0 (0.7)	44.3 (39.7)	0.435 (0.10)	7.05
	15–30	6.7 (0.7)	5.6 (0.8)	45.4 (52.8)	0.328 (0.05)	7.44
Mb	0–5	6.5 (0.4)	5.7 (0.4)	41.0 (6.4)	0.945 (0.24)	11.12
	5–15	6.9 (0.3)	5.8 (0.4)	18.4 (3.7)	0.585 (0.15)	8.93
	15–30	6.7 (0.2)	5.5 (0.3)	18.3 (4.4)	0.493 (0.09)	10.00
Mp	0–5	8.1 (0.2)	7.1 (0.2)	45.1 (8.2)	0.315 (0.04)	8.00
	5–15	8.1 (0.2)	7.1 (0.2)	45.9 (16.3)	0.250 (0.06)	7.46
	15–30	7.6 (0.2)	6.6 (0.2)	43.1 (14.6)	0.243 (0.05)	8.36

EC, electrical conductivity.

the suspensions were homogenized after which 100 ml suspension was taken and siphoned after specific time intervals and from appropriate depths to produce aliquots of the < 20 μm and the < 2 μm fractions. All suspensions were flocculated with calcium chloride and excess salt in the suspension removed by washing. All fractions were freeze-dried, after which they were oven-dried at 60°C for 24 hours and weighed. Thus, for each individual field representing a specific land use history on a specific soil, four replicate < 2 mm samples were fractionated.

Chemical analysis

Total C and N were determined in duplicate for all size fractions using an EL Micro Elemental Analyser. The ^{13}C isotopic analysis was performed using a Carlo Erba 1500 Elemental Analyser in combination with a Micromass Optima continuous flow isotope ratio mass spectrometer. The ^{13}C abundance in an equivalent mass of sample containing at least 300 μg C was determined in the CO_2 obtained by combustion in sealed quartz tubes with CuO at 900°C. The evolved CO_2 was purified and analysed on the isotope ratio mass spectrometer. The local reference material GS-7 (sucrose) was used as both the elemental and isotopic standard (Gonfiantini *et al.*, 1995). Results are expressed as δ^{13}C (‰) with respect to the VPDB (Vienna Pee Dee Belemnite) calibration material (Coplen, 1995). Since δ^{13}C is a small number under all natural circumstances, it is usually expressed in ‰:

$$\delta^{13}\text{C‰} = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 1000, \tag{1}$$

where R is ^{13}C/^{12}C. In total, 160 samples were analysed in five batches. Each batch contained samples, references and blanks, the numbers of sample versus reference being typically 5:1. Since the organic carbon content was known beforehand, the amount of sample could be chosen such that the amount of carbon present was about the same for all samples and references, around 300 μg. For those samples with very low carbon contents (< 0.3%), the maximum amount of sample (100 mg) did not allow for this amount of carbon. In the batch containing these samples, the amount of reference material was also reduced. The total precision of each individual sample (including calibration and blank subtraction errors) using this procedure was better than ± 0.15‰. This number is based on long-term monitoring of the instrument's behaviour using various reference materials.

Statistical analysis

For each soil type, the level of significance of the differences between group means of δ^{13}C values in each size fraction was determined. Additionally, the significance of differences in δ^{13}C values between sand and finer-sized fractions was determined separately for each land use history. The data were analysed by one-way ANOVA, followed by multiple comparisons of the LSD test at $P = 0.05$ (SPSS, version 9).

Results

Analytical methods

The total error for each individual isotope analysis is less than ± 0.15‰, which for the δ^{13}C values of the samples analysed translates into coefficients of variation (CV) of below 1%. The CVs given in Table 3 pertain to the overall error, including effects of soil heterogeneity, and indicate that for most samples soil heterogeneity contributes about 50–70% of the total observed spread of values. We calculated the δ^{13}C values for bulk soil (< 2 mm) based on weighted δ^{13}C values for the 0–53 μm and 53–2000 μm size fractions. Comparison of calculated and measured δ^{13}C values for < 2 mm fractions provides a test for the reliability of the combination of methods used (Figure 1). The average difference is −0.04 ± 0.16‰ (error of the mean), while the standard deviation of the difference is 0.4–0.5‰.

Measured δ^{13}C values were used with particle-size distributions of the organo-mineral fractions to calculate δ^{13}C values in the fine silt (2–20 μm) fraction (Table 3). For the 20–53 μm fractions, such calculation resulted in values with large CVs, probably due to accumulation of small analytical errors. Consequently, calculated values for this fraction were discarded. It should be stressed that the particle-size distribution of the organo-mineral material differs considerably from the

Table 3 δ^{13}C values (‰) of organo-mineral size fractions ($n = 4$ for all fractions except < 2 mm, where $n = 2$)

Field		< 2 mm	0–2 μm	2–20 μm	0–20 μm	0–53 μm	53–2000 μm
Vm	Mean	−16.4	−16.2^{a}	−16.1^{a}	−16.0^{a}	−15.8^{a}	−16.9^{a}
	CV	1.0	2.0	3.1	1.3	6.8	
Vf	Mean	−21.6	−19.5$^{c/x}$	−20.6$^{c/y}$	−19.9^{c}	−19.7^{c}	−25.8$^{c/z}$
	CV	1.3	2.6	0.8	1.2	2.1	
Vc	Mean	−18.1	−17.3$^{b/x}$	−17.3$^{b/x}$	−17.3^{b}	−17.5^{b}	−22.2$^{b/y}$
	CV	2.1	2.3	0.7	0.4	5.3	
Lf	Mean	−18.7	−17.0$^{b/x}$	−17.5$^{b/y}$	−17.3^{b}	−17.5^{b}	−20.6$^{c/z}$
	CV	0.5	1.3	0.9	1.1	0.7	
Lr	Mean	−17.0	−16.4$^{a/x}$	−16.8$^{a/x}$	−16.6^{a}	−17.1^{a}	−18.0$^{a/y}$
	CV	1.0	2.9	1.3	0.7	0.4	
La	Mean	−18.1	−17.2$^{c/x}$	−17.8$^{b/y}$	−17.5^{b}	−17.7^{b}	−18.4$^{b/z}$
	CV	0.8	1.1	0.5	0.8	1.4	
Mt	Mean	−14.1	−14.1$^{b/y}$	−13.5$^{b/x}$	−13.8^{b}	−14.5^{b}	−14.1$^{b/y}$
	CV	2.8	3.0	0.6	1.4	1.8	
Mb	Mean	−13.4	−12.7$^{a/x}$	−13.0$^{a/x}$	−12.9^{a}	−13.6^{a}	−13.5$^{a/y}$
	CV	3.3	2.9	1.6	2.7	0.8	
Mp	Mean	−14.8	−14.3$^{b/x}$	−14.0$^{b/x}$	−14.2^{c}	−14.8^{b}	−18.5$^{c/y}$
	CV	1.3	3.3	1.6	1.5	0.9	

Significant differences ($P < 0.05$) between mean values of specific size fractions from the same soil type (V, L or M), but from different fields, are indicated with the letters a, b and c; significant differences ($P < 0.05$) in mean values between different size fractions (0–2, 2–20 and 53–2000 μm) from the same field (e.g. Vm) with the letters x, y and z. Coefficient of variation (CV) is in %.

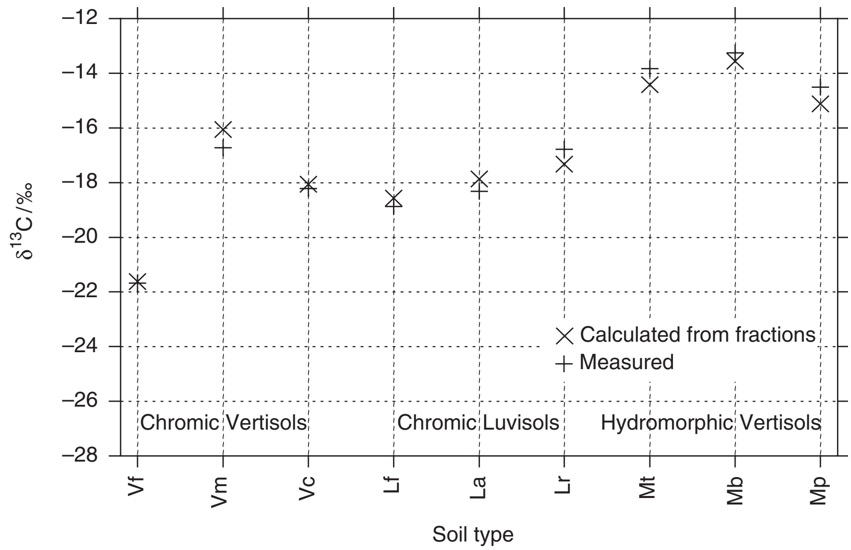

Figure 1 Measured and calculated δ^{13}C values for the fine earth fractions (< 2 mm). Calculated values are based on measured values for the fractions < 53 μm and 53–2000 μm ($n = 4$).

particle-size distribution of the mineral fraction as obtained after destruction of organic matter (Table 4), illustrating the role of organic matter in soil aggregation.

The CVs of the δ^{13}C values were generally < 2% for individual samples, with some exceptions of about 3%. As to the calculated values for the fractions 2–20 μm, the use of all values resulted in some relatively high CVs, but when outliers were excluded, the CVs dropped to < 3%.

Analytical data

Soil organic carbon (SOC) contents and δ^{13}C values are presented in Tables 3 and 5. SOC contents of the < 2 mm fractions were distinctly greater in fallow soils (Vf and Lf) and smallest in soils that were ploughed or intensely cultivated (cf. Mt and Mb versus Mp). In the fields on the Chromic Vertisol, the smallest δ^{13}C value occurred in the fallow soil (Vf) and the greatest in the Muskwari soil (Vm), while in the Chromic Luvisol a similar but less prominent trend was observed. In the fields on the Hydromorphic Vertisol under various types of Muskwari, the ploughed soil (Mp) had much the smallest SOC

Table 4 Particle-size distribution (in mass %, $n = 4$). Present and Absent refer to removal of soil organic matter (SOM; see text)

Field	SOM	< 2 μm	2–20 μm	20–53 μm	53–2000 μm
Vm	Present	33.2	14.0	17.5	35.3
	Absent	47.6	17.3	3.3	31.8
Vf	Present	37.2	14.7	16.5	31.5
	Absent	38.2	20.1	3.1	38.6
Vc	Present	26.4	9.0	17.7	46.9
	Absent	47.0	15.1	1.9	36.1
Lf	Present	7.7	13.2	19.3	59.8
	Absent	26.0	10.7	3.2	60.1
Lr	Present	8.7	12.7	22.1	56.6
	Absent	23.8	16.6	3.8	55.9
La	Present	7.0	9.0	16.7	67.3
	Absent	17.1	10.8	3.9	68.2
Mt	Present	30.8	10.7	17.2	41.2
	Absent	43.8	13.3	4.1	38.9
Mp	Present	36.5	17.9	13.5	32.1
	Absent	48.5	19.5	4.7	27.3

Table 5 Organic carbon content in organo-mineral size fractions ($n = 4$)

Field		Organic carbon content /%			
		< 2 μm	2–20 μm	0–20 μm	53–2000 μm
Vm	Mean	0.919[a]	1.306	1.033	0.459[b]
	CV	2.4	6.3	2.2	15.6
Vf	Mean	0.997[b]	1.578	1.162	0.861[c]
	CV	3.7	7.3	3.5	12.2
Vc	Mean	1.029[b]	1.280	1.094	0.128[a]
	CV	2.1	27.0	8.8	3.9
Lf	Mean	4.659[c]	3.242[c]	3.761[c]	0.651[c]
	CV	1.5	0.7	0.2	2.2
Lr	Mean	2.806[a]	1.656[a]	2.123[a]	0.214[a]
	CV	4.0	9.1	3.1	4.8
La	Mean	4.058[b]	2.646[b]	3.264[b]	0.296[b]
	CV	4.3	8.6	1.9	5.3
Mt	Mean	0.851[b]	1.567[b]	1.036[b]	0.391[c]
	CV	8.6	7.5	4.1	3.2
Mb	Mean	1.501[c]	2.650[c]	1.880[c]	0.279[b]
	CV	1.6	20.9	9.3	4.3
Mp	Mean	0.670[a]	0.837[a]	0.715[a]	0.104[a]
	CV	1.5	19.0	6.7	8.1

Significant differences ($P < 0.05$) between mean values of specific size fractions from the same soil type (V, L or M), but from different fields, are indicated with the letters a, b and c. Coefficient of variation (CV) is in %.

content and at the same time the smallest δ^{13}C values, while these were greatest in the bunded soil (Mb).

As to the fractions, the general trend was that finer size fractions (clay and fine silt) were ^{13}C enriched compared with sand fractions, and differences were generally statistically significant. Furthermore, the greatest land-use related differences in δ^{13}C values occurred in the sand fractions with the smallest values in the fallow soils. SOC contents were smallest in the sand fraction of all soils and in this fraction showed the strongest decline upon intensive cultivation, particularly ploughing.

When summarized by soil type, the results are as follows (Tables 3 and 5).

Chromic Vertisol. In all size fractions, the Muskwari soil (Vm) had significantly greater δ^{13}C values than the fallow (Vf) and cotton (Vc) soils. In the latter, the δ^{13}C value in each size fraction was intermediate between those in corresponding size fractions of the Muskwari and fallow soils.

Chromic Luvisol. In all size fractions, the cropped soil (Lc) had significantly higher δ^{13}C values than the agroforestry (La) and fallow (Lf) soils. Significant differences in this value between the Lf and La soil were limited to the sand fraction, being smaller in the Lf soil.

Hydromorphic Vertisol. In all size fractions of the bunded soil (Mb), δ^{13}C values were significantly greater than in the traditional (Mt) and ploughed (Mp) soils. Additionally, the sand fraction in the Mp soil had a significantly smaller δ^{13}C value relative to the other soils.

Discussion

Fine earth fractions

In the Chromic Vertisol, the significantly greater SOC content of the fallow (Vf) soil with the smaller δ^{13}C value clearly points to a greater and more C_3-plant derived input relative to the Muskwari soil (Vm), as can be expected for this land use type. The results demonstrate that changes in land use may affect the SOC content, but not always so (e.g. Vm versus Vc) and that the SOC content of the < 2 mm fraction is a poor indicator of SOC turnover rates. Eight years of cotton in rotation with sorghum was sufficient to change the δ^{13}C value from about -16‰ to about -18‰ and 8 years of fallow produced a change to about -22‰.

A similar trend occurs in the Chromic Luvisol. The La and Lr soils received a mixture of litter from C_4 and C_3 plants and both had smaller SOC contents and δ^{13}C values than the fallow soil (Lf). However, differences in δ^{13}C values are much smaller, suggesting that current land use might be less important or that, under fallow (open savannah), part of the litter was derived from C_4 plants and thus the δ^{13}C value of the litter input into the various soils differed little.

In the Hydromorphic Vertisol, the impact of ploughing (Mp) was remarkable, clearly causing a major reduction in SOC and at the same time a shift towards less prominent C_4-plant litter input. The latter can be related to the impact of ploughing on weeds, the dominant weed on non-ploughed soils being *Setaria pumila* grass (C_4 plant), while in ploughed fields herbs (C_3 plants) are much more common and are regularly incorporated into the soil. Water harvesting (Mb) seems to lead to a greater SOC status and also to a slight shift towards more C_4-plant derived litter, which is not surprising since greater water availability leads to greater standing biomass (crop and weed) and presumably greater litter input. Thus here too, the dynamics of SOC involve more than a simple decline or increase in its content, the changes in δ^{13}C value showing a more dynamic behaviour of that carbon.

The above statements have to remain quite tentative since we lack data on the isotopic composition of the litter input and its various components. Moreover, the potential impacts of the two processes mentioned in the Introduction (isotopic fractionation during mineralization and isotopic heterogeneity in the litter components) cannot be judged. Furthermore, the results do not allow for a check of current ideas about the size-related stability of soil organic matter in these types of soils.

Size fractions

Decomposition and biodegradation of litter produce particulate organic matter (Cambardella & Elliott, 1993, 1994; Shang & Tiessen, 1998; Six *et al.*, 1998), which in time is transformed into finer material that is often protected against further decomposition by mineral components. Though part of the litter input will be of small, even minute, size and be directly incorporated into the finer fractions, e.g. root fragments, the δ^{13}C value of the clay and fine silt fractions will adapt more slowly to changes in input and reflect the provenance of the longer-term litter input. In this complex process, δ^{13}C values of specific size fractions might be affected by isotopic fractionation or isotopic heterogeneity of the litter input.

Isotopic fractionation and isotopic heterogeneity of the litter should show up in soils in which (near) equilibrium conditions exist for soil organic matter decomposition. Such conditions may be approached in the Vm and Mt soils, where the vegetation or land use has been the same for a very long time (> 70 years monoculture) under conditions of very rapid and intensive turnover of the litter input, resulting in (very) small equilibrium SOC values. In both soils, the size fraction related variation in δ^{13}C value in the fractions is very small (0.9‰ in Vm and 0.6‰ in Mt). This shows that the processes indeed have a very limited impact on the size-dependent isotopic composition of the SOC in the soils concerned, if any impact at all. Thus, if relatively large changes in isotopic composition of SOC size fractions occur upon a change in land use, these have to be explained as being due to direct and indirect (derived from coarser size fractions and thus secondary) input of material with a deviating isotopic signature. The clearest indication for such input will be found in the sand fraction, assuming that sand-size organic matter reflects the most easily decomposable and thus most recent organic matter. Based on these observations and arguments, results for the individual series of fields can be described and interpreted in terms of changes in input (C_3 versus C_4 plants) and in turnover rates of SOC in the various size fractions.

Chromic Vertisol

The δ^{13}C values of around -16‰ in the various fractions of the Muskwari soil (Vm), with continuous sorghum cultivation for > 70 years, are within the range for δ^{13}C values for plants of C_4 origin and are assumed to reflect the (near) equilibrium conditions, with regard to both SOC content of the various size fractions and their isotopic composition. Annual shrubs and weeds that thrive during the rainy season on these Muskwari soils and are burned prior to the cultivation of sorghum are mostly C_3 plants. Their temporary (seasonal) input – mainly of roots – might well explain the slightly smaller δ^{13}C value of the sand-size SOC fraction.

In the Vc soil (cotton), the sand fraction in particular is affected by this land use, with a serious decline in SOC and its δ^{13}C value, while the other fractions seem to be hardly affected and have δ^{13}C values resembling those of the Vm soil. Since cotton was the last crop, it seems most probable that coarse debris from this crop dominates the sand fraction, whereas in the finer fractions the δ^{13}C value most probably reflects the longer-term input in which sorghum-derived organic matter is a major component. This is strongly supported by the small differences in δ^{13}C values of the clay and fine silt fractions between the Vm and Vc soils.

In the fallow soil, the finer fractions apparently contain a mixture of C_3- and C_4-plant derived organic matter for which the most likely explanation seems that the fallow period has been too short to lead to a full replacement of sorghum-derived organic matter (> 60 years Muskwari before 8 years of fallow). Here too, the differences in δ^{13}C values between the fractions and relatively smaller changes in their SOC contents clearly indicate that in this soil fine organic matter is considerably more stable and its concentration adapts more slowly to changed inputs than the coarser fraction and reflects the longer-term rather than the current input.

Chromic Luvisol

Impacts of land use on SOC extend into the fine fractions, even the clay fraction being significantly affected, though impacts are greatest in the sand fraction. These impacts are not reflected in major changes in δ^{13}C values, the major differences being slightly higher δ^{13}C values for the cereal crops soil (Lr), which can be attributed to a relatively large contribution of sorghum litter to the SOC pool, and a relatively low δ^{13}C value of the sand-size SOC for the fallow site (Lf). In fact, the same trend – somewhat lower δ^{13}C value in the sand-size SOC – is observed in the other soils. Possible explanations are that the vegetation, which in all fields has a mixed C_3–C_4 composition, produces litter that in the coarser fraction is somewhat more C_3-plant derived (e.g. woody debris) or seasonally has a relatively high root input by C_3 plants.

Evidently, upon cereal cropping (Lr) SOC declines in all fractions and additionally is partly replaced by sorghum-derived SOC. In the other soils, changes in SOC content occur, but whether these are accompanied by replacements within these fractions is not clear. Lastly, though it is evident that SOC contents of the finer fractions vary considerably with changes in land use and thus point to a quite dynamic SOC pool, these values are large relative to those of the corresponding fractions in the other soils and thus at the same time point to a relatively large capacity of the clay and fine silt fractions of these soils to bind SOC. This is in line with results from other studies on similar Chromic Luvisols in the tropics (e.g. Wattel-Koekkoek *et al.*, 2003).

Hydromorphic Vertisol

As stated above, the traditional Muskwari soil (Mt) is considered to be in (near) equilibrium and thus to reflect the 'standard' SOC size distribution and its isotopic composition in this soil and under this land use. Its δ^{13}C values are typical of C_4 vegetation, which is not surprising since the vegetation (sorghum and grasses) consists largely of C_4 plants. Contents and distribution of SOC are virtually identical to those in the other Vertisol with prolonged Muskwari (Vm).

Bunding, aimed at water conservation, results in a considerably increased biomass production and concurrent increased litter input reflected in an increased SOC content of all size fractions. The significantly greater δ^{13}C value of all fractions points to a larger input of C_4-plant derived organic matter, as already discussed above, and a relatively fast turnover of this litter.

Ploughing leads to a serious decline in SOC content in all size fractions, in line with observations by many other authors on the impact of ploughing (e.g. Balesdent *et al.*, 1988). The latter is in contrast to the trend in the Chromic Vertisol (Vc) where SOC in the finer fractions is much less affected. It is the input from the C_3 weed species that replaces *Setaria pumila* grass to which the decline in δ^{13}C values in the sand fraction must be attributed. In other words, the SOC in the various size fractions not only declines strongly, but is also partly replaced by 'fresh' SOC, showing that SOC fluxes in this soil are large relative to those in the Chromic Vertisol.

General discussion

In the Chromic Luvisol, major changes in SOC occur in all size fractions upon intensive cultivation (including ploughing). Differences in isotopic composition of the litter input under the various land use histories are insignificant, and do not show up in clear changes in isotopic composition of size fractions that could provide additional information on longer-term SOC turnover.

In the case of the Vertisols, these differences in isotopic composition of the litter input are clearly much greater and indeed show up in the various size fractions, but marked differences in turnover were observed between the soils. In the Chromic Vertisol, the finer SOC fractions seem to be very stable and hardly affected by land use (within about 10 years), pointing to a slow turnover of SOC present in the finer fractions. In the Hydromorphic Vertisol, SOC fractions adapt much more rapidly (within 20 years) to changed litter input and conditions. X-ray analysis showed that in the Chromic Vertisol the clay fraction is dominated by hydroxy Al-interlayered smectite, whereas in the Hydromorphic Vertisol smectite dominates, but lacks the prominent hydroxy Al-interlayering (Obale-Ebanga, 2001). Furthermore, though not being 'Pellic', the Chromic Vertisol has the characteristic dark colour indicative of strong clay–organic matter bonds observed in such Vertisols (Bocquier, 1973; Duchaufour, 1982), whereas the Hydromorphic Vertisol is of very recent age and lacks this dark colour. These data suggest that differences in age and mineralogy, notably the hydroxy-Al interlayering, might result in differences in SOC turnover, as also observed by other authors (Feller *et al*., 1991, 1996; Roscoe, 2002). It should be stated that Wattel-Koekkoek *et al*. (2003) concluded that the mean residence time of fine soil organic matter in the clay fraction of their smectitic Pellic Vertisols is very great (1100 years), in sharp contrast with our results for the Hydromorphic Vertisol. However, their Vertisols were all Pellic (black) and presumably of a much greater age than the Hydromorphic Vertisol studied by us, which still receives fresh sediment regularly.

Size fractionation and isotopic analysis of the fractions indeed provided more detailed information on SOC turnover in relation to land use history, but only in rather qualitative terms. Our data do not allow for a true quantification of turnover rates of organic matter in the various size fractions.

Conclusions

The methodology used appears to produce reliable and accurate results on the δ^{13}C values of these tropical savannah soils that are characterized by their very small organic matter contents. Furthermore, the use of size fractions appears to be essential for a better understanding of SOC dynamics in relation to land use for such soils.

The major impact of land use is on the sand-size fractions, where a relatively rapid adjustment to the litter sources can be seen, i.e. within less than a decade. This turnover is even more rapid than suggested by the changes in organic matter content only (Obale-Ebanga, 2001), as evidenced by the changed isotopic composition of this organic matter. The impacts on the finer fractions are less prominent, but here too changes in isotopic composition of the litter can largely explain the observed changes in isotopic composition. Furthermore, impacts on these finer fractions differ among the soils, the stability of the SOC probably being affected by the soil mineralogy, with more stable SOC in the older Chromic Luvisol and Chromic Vertisol, and distinctly less stable SOC in the recent, smectitic Hydromorphic Vertisol.

The relation between land use type and δ^{13}C value is less straightforward than a simple relation with crop type (C_3 or C_4). Weeds (C_4 grasses or C_3 herbs) and land management (burning versus non-burning, tillage versus zero tillage, sowing versus transplanting for sorghum) were found to play an important role. Rather than crop type, it is where and what litter enters the soil that determines the carbon isotopic signature of SOC, particularly in the sand-size fraction. For the latter, even the time of sampling within a rotational scheme appears to have a major impact, illustrating that turnover rates of such coarse organic matter may be in the order of a cropping season or even less.

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